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THESIS

FORMAL PROCESS MODELING TO IMPROVE HUMAN DECISION-MAKING DURING TEST AND EVALUATION RANGE CONTROL

by

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September 2017

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This thesis explores how formalization of these experience-based decisions as a process model representing a T&E event may reveal high-value decision nodes where certain decisions carry more weight or potential for impacts to a successful test. The thesis evaluates behavioral modeling techniques and language, ultimately using the Innoslate modeling software tool to construct a formal model of the range decision process. The thesis presents the results of the simulation runs in Innoslate and shows how having the formal model improves on the simplified model by expanding the process from two to eleven decision points. The thesis concludes that the formal model has use as a planning tool that can assist mangers in anticipating problems and focusing resources on resolving these issues.

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FORMAL PROCESS MODELING TO IMPROVE HUMAN DECISION-MAKING IN TEST AND EVALUATION ACOUSTIC RANGE CONTROL

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ABSTRACT

Test and evaluation (T&E) managers often control testing via heuristics (i.e., using experience and lessons learned from previous testing to modify existing range control procedures). An exclusively heuristic approach may prove difficult in predicting test control issues with new systems. Given this limitation, this thesis poses the following question: Can formally modeling the process of conducting test range events expose previously overlooked ambiguities and identify high-value decision points?

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LIST OF ACRONYMS AND ABBREVIATIONS

BPM	Business Process Modeling
DT&E	developmental test and evaluation
NAVSEA	Naval Sea Systems Command
NUWC	Naval Undersea Warfare Center
OT&E	operational test and evaluation
RO	range officer
RP	run plan
RDTE	research development test and evaluation
TD	test director
T&E	test and evaluation
UUT	unit under test
UUV	unmanned underwater vehicle

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EXECUTIVE SUMMARY

Acoustic range managers need a better system or process for identifying high-value decision points before conducting test events. At the time of this research, a qualitative process model that represents the acoustic range decision process did not exist. This thesis reviewed decision-modeling literature to evaluate possible models and applications for representing the decision processes of an acoustic range test event.

The research focused on modeling the decision process of the Naval Undersea Warfare Center (NUWC) Division, Keyport, underwater acoustic tracking range. The model had to be capable of replicating a simplified version of an event, so test planners can see the identification of high-value decision nodes and use this information to make better decisions regarding risk management and mitigation. Research focused on developing a basic understanding of the decision methods, developing an appropriate model, and then simulating the decision process to identify high-value decision points.

Range managers relied on heuristics to predict problem areas, which do not always provide useful risk analysis tools for new testing programs that may require different evaluation constructs. Additionally, the range did not employ quantitative risk analysis techniques, which could have identified problem areas before testing. The author focused on providing a formal model that could provide these capabilities and addressed the following question: Can formally modeling the business process of conducting test range events expose previously overlooked ambiguities and identify high-value decision points?

Next, the thesis assessed a proposed formalized decision process capable of representing a simplified range event and used the following measures of merit to evaluate the effectiveness of the formal model:

- The number of high-value decision points reflected in the formalized process model exceeds the number of high-value decision points in current informal process models of range event activity. High-value decision points reflect specific places in the test process that if improperly executed, could result in loss of test data or prematurely aborting the test.

- The formal model displayed at a minimum the decision points found in the simplified model. The formal model improved on the simplified model by providing more decision points, which represented the test event more accurately.

Model variables included the number of decision nodes and the number of uses of a decision node during the simulation run. Multiple uses of the same decision node indicated a high-value decision point. Confirmation of high-value decision nodes occurred during model validation. The following two points summarize the risks and uncertainties:

- Since the acoustic range studied had never modeled their decision process, the ability to replicate the informal process as a formal model via a simulation program was uncertain. Ultimately, the thesis identified a suitable program that adequately represented the range decision process.

- Similarly, the ability of the formal model to identify high-value decision points in the test decision process was unknown. In the course of building the formal model, methods provided by the software program allowed counting decision node usage, which in turn provided information on the value of each decision in the process model.

Current business process modeling (BPM) methods were evaluated. The author evaluated the simulation of the range process model using the selected process model software. Aspects observed included logical flow of events, event duration, decision probabilities, number of uses of each decision node, accuracy of feedback loops, and overall utility of the model to range managers. Additionally, the author shared the model simulation and results with range managers and received feedback that the range could use the product when conducting event planning, and risk assessments.

The thesis evaluated the current modeling approaches used by the acoustic range through the collection of relevant decision and process data used to control range events. The main sources were existing range control policy documents and information collected from range managers.

The thesis documented the development of a simplified block-diagram model representing a routine acoustic range event. The thesis developed a formal process model using simulation software capable of replicating the simplified process model. Conduct of multiple model runs determined that the model could identify high-value decision nodes.

Observation of modeling runs assisted in determining whether required the formal model adequately replicated feedback loops and processes performed the range operators. Model runs showed the actual sequence of expected high-value decision points in the test event process. The simulation software generated reports providing data on the number of uses of each decision point during a simulation run.

At the conclusion, the thesis defined that a high number of uses of the same decision point throughout the modeling runs indicated a high value, as the range operators would have multiple opportunities to make the decision. Therefore, the higher number of times a range operator encountered that decision, the higher the probability that an incorrect choice at that point could negatively affect the test run. The model had sufficient discrimination between decisions to provide clear indications as to which decisions points had high value according to the definition.

The capability of the model to adjust decision choice probabilities provided the ability to observe changes in the number of uses of each decision, indicating the model had sufficient sensitivity to show how the accuracy of choice probabilities affect identification of high-value decisions. Test and evaluation subject matter experts and managers from the Naval Undersea Warfare Center Division, Keyport, reviewed the model execution and modeling run results. They concluded the model has application to range test event planning and with further refinement, could assist test planners and range managers in predicting potential risk areas during range events. Additionally, the model could assist managers in assessing new test programs prior to their first test runs, providing advance insight as to where problems might occur.

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I. INTRODUCTION

The purpose of this chapter is to present problems faced by undersea test ranges in the area of human decision-making and the lack of pre-test quantitative analysis tools available to assist range operators in identifying and reducing decision risks. This chapter identifies problem areas and their effect on the conduct and control of acoustic test events and addresses why improvements in these areas would benefit range managers and operators. Additionally, this chapter presents the thesis research questions and research methodology. The expected product of the research is discussed, specifically, the development of a formal model that simulates the decision-making process of a test and evaluation (T&E) event on an underwater tracking range. The chapter also explores the need for a repeatable method that can formalize simplified decision model process charts.

A. PROBLEM BACKGROUND

Underwater acoustic test and evaluation ranges support developmental test and evaluation (DT&E) and operational test and evaluation (OT&E) necessary for undersea weapons and systems development. Control of range operations includes procedures to regulate range operations through systematic control of activities such as the loading and launching of high-speed test vehicles. These range-event operations also include free-play approaches such as providing a controlled test area for autonomous unmanned underwater vehicle (UUV) operations. According to Brian Adams, range manager for the acoustic range at NUWC Division, Keyport, planning for these events has historically followed a heuristic approach, (i.e., lessons learned over years of operating the range influence the planning and conduct of subsequent tests). Event planners use this experience to develop test plans that will accomplish program objectives while minimizing risks to the units under test (UUT), personnel, and range equipment (Brian Adams, pers. comm. November 20, 2016). This method has been sufficient for test control of well-understood systems such as current torpedoes and submarines. However, this approach may not be adequate to provide acceptable risk management for increasingly sophisticated systems such as autonomous UUVs and new generation undersea weapons. Bodmer (2003) discussed the need for test and evaluation methodology to remain transformational, and that testing must be as early in the life cycle as possible to lower cost. The current range event planning approach may not be sufficient to support Bodmer's recommendation. Discussion with the NUWC Division, Keyport Range Manager identified the following shortfalls in the current heuristic test planning approach:

- lack of pre-event analysis tools
- lack of quantitative risk assessment methods
- unavailability of predictive models
- in situ decision-making limitations
- increased cost of poor decisions

1. Lack of Pre-test Event Analysis Tools

At present, event planners have no analysis tools that assist them in predicting critical points during the test event when key decisions may be likely. Planning for tests currently involves the development of a run plan (RP) that sets the sequence of events during the test, provides parameters for sensors and test equipment, and provides overall instructions to range operators supporting the test. Planners use qualitative risk analysis tools when developing the RP and mitigate risk by following best practices learned from previous tests, according to the NUWC Division, Keyport Range Manager. When encountering a problem during testing, range managers conduct inquiries into the root causes of the problem and then develop new policies, processes, or procedures designed to prevent recurrence of the issue. Managers apply these changes to the RP process if warranted. The NUWC Division, Keyport Range Manager also stated that at present, the range has no prescribed procedures for developing test plans other than using this standardized run plan format.

2. Lack of Quantitative Risk Assessment Methods

Risk assessments tend to be qualitative and focus on procedural compliance and centralized control of the test event by one individual, the range officer (RO). According to NUWC Division, Keyport Range Manager, the ability of the RO to keep track of test parameters limits the speed of execution and maximum scope of the test event. He further stated not all RO candidates display the necessary aptitude to control highly complex tests.

According to the NUWC Division, Keyport Range Manager, test control currently relies on a countdown-like procedure with periodic stopping points that provide intentional delays during the test event, allowing the RO to review preparations and evaluate readiness to move to the next phase. The RO authorizes the commencement of each phase of the procedure, and does not start the next phase until all steps of the current phase are complete. Most tests follow a regimented procedure to assist the RO in controlling the test. Historically, range operators have not quantitatively identified or catalogued high-value decision points that occur during acoustic test events. High-value decision points are those situations during the test event in which a poor decision could result in the unnecessary aborting of the test, loss of test data, damage to the unit under test (UUT), or damage range testing assets. He also indicated that the lack of any pre-test event decision analysis requires that ROs make decisions in situ using experience and heuristic-based procedures.

3. Unavailability of Predictive Models

The acoustic range does not use modeling or statistical analysis of decision processes in its test planning, nor is any quantitative risk analysis performed. The testing of torpedo software uses simulation, but this analysis is independent of range operations. According to the NUWC Division, Keyport Range Manager, predictive modeling of decision processes or effectiveness has not been evaluated using statistical techniques. Analysis of completed test events to identify decision points is untried. He noted his range managers are unaware if such approaches would be of benefit.

4. In Situ Decision Limits

The NUWC Division, Keyport Range Manager noted that Range Officer training focuses on recognizing and understanding normal and expected conditions for the particular test and on using information from displays and reports from other range technicians to determine if the test is proceeding as planned. If the test run deviates from the plan, the range officer must make the decision either to continue the test as planned, to modify the plan, or to abort the test. RO training requires aborting of tests only if it becomes clear the vehicle or range personnel will become at risk; otherwise, the RO will attempt to alter test parameters to achieve as many test objectives as possible. He also stated a major purpose of the RO training process is to assist the RO in recognizing abnormal conditions that require intervention, but that ROs develop this skill more thoroughly through actual experience gained after qualification.

5. Increased Cost of Poor Decisions That Result in Loss of Test Data

Test and Evaluation events that do not produce the data required by the program can result in delays to development schedule or increased cost of testing if critical data is still required. Developmental test and evaluation (DT&E) events are usually earlier in the program cycle and often have a limited budget (AcqNotes 2016). The NUWC Division, Keyport Range Manager stated acoustic range events are expensive given the cost of test vehicles, range craft, and the personnel labor required for planning and conduct of on-water tests. Additionally, reductions in DT&E and OT&E budgets have forced program managers to reduce testing, which, in turn, increases the value of remaining tests in terms of achieving program test objectives. As the purpose of DT&E testing is to decrease overall cost through early discovery of failures and defects (Test Resource Management Council 2017), acoustic range test failures can add significant cost and schedule delays to programs.

These factors place increased burden on the test facility to conduct accurate and successful tests that produce the intended test conditions, which in turn raises the pressure on test planners to predict and mitigate potential test problems. Additionally, there is increased burden on ROs to identify quickly emergent problems during testing and take prompt action to salvage test objectives and protect program test assets. If these efforts fail, programs can lose critical data, which can result in repeating an expensive test event. Therefore, poor decisions by range planners and operators can severely affect programs by wasting scarce schedule and funding resources.

B. PROBLEM FORMULATION AND RESEARCH OBJECTIVES

The problem faced by Range Managers and test planners centers on the scarcity of predictive tools that allows range personnel to anticipate high-value decisions in their test process. The high cost of DT&E and OT&E testing means programs often have diminishing resources to conduct tests, therefore each test has increasing value in producing useful data. Range managers require a method capable of analyzing current test events for improvements as well as predicting potential issues for T&E of new systems.

Given the shortfalls of the current heuristic test planning approach described in the previous section, the objectives of this thesis are to:

- Identify a formalized process model that accurately describes the decision process used to control a simplified acoustic range event.
- Evaluate the utility of this model for assisting the range manager in conducting pre-event decision analysis and risk management.

This thesis poses the question: can formally modeling the business process of conducting test range events expose previously overlooked ambiguities and high-value decision points? To support conclusions about this question, the thesis will compare the number of unique decision points and the total number of events in each model.

C. RESEARCH METHODOLOGY

The basic approach of the thesis research methodology is to:

- Conduct an analysis of possible decision modeling approaches that could assist acoustic range test planners in identifying high-value decisions that occur during test events.
- Identify a simplified process model that represents the current acoustic range test event decision methodology.
- Create a formal process model that improves on the simplified decision model through the use of a formal model to determine if high-value decision nodes can be identified and planned for in advance of test runs.
- Recommend possible uses of the model to assist range event planners.

D. THESIS ORGANIZATION

Chapter I introduces the problem faced by test range managers and posed the research question the thesis researched.

Chapter II reviews business process modeling literature and selects a suitable approach for documenting the current decision process of the test range at NUWC Division, Keyport.

Chapter III analyzes current NUWC Division, Keyport range decision-making processes, proposes a simplified model to represent current decision approaches, and identifies weakness in the model requiring improvement.

Chapter IV develops a formalized model of the range decision process, discusses model runs within the selected software tool, and provides information generated from completed model runs.

Chapter V analyzes results of model execution and provides conclusions on the usefulness of the model to range managers. The chapter concludes with recommendations for model improvement and further study.

II. REVIEW OF BUSINESS PROCESS MODELING LITERATURE

This chapter reviews decision-modeling literature with the purpose of identifying approaches or languages that would assist in modeling the business and decision-making process of conducting an acoustic range test. The chapter describes a sample of current modeling approaches and provides evaluation of potential choices to represent decision processes used during acoustic range T&E events. Examination of other process models includes review of potential utility for assisting thesis research. The chapter concludes with the selection of potential models or processes that will assist in modeling a simple acoustic T&E event.

A. BUSINESS PROCESS MODELS

Business process models (BPM) or process modeling is a type of workflow concept that separates work activities into defined tasks, roles, and procedures that describe that organization's method of fulfilling customer needs (Georgakopoulos, Hornick, and Sheth 1995). Process models range in complexity from simple two-dimensional workflow charts to customizable software simulations.

1. Process Model Approaches

Several process models are available that are capable of representing complex systems. The following sections describe and evaluate potential business process models (BPMs) that could potentially serve as a process for range event decision-making.

a. Business Process Modeling and Notation

Business process modeling and notation (BPMN) is a process diagram approach using on flowcharting methods to create graphical representations of business processes (White 2004; Reisig 2013). White notes that use of graphical elements allows for simple diagrams that still capture complex business processes, and that limiting the diagram elements to a small of number shapes and connectors precludes modelers having to learn complex notation. BPMN is a modeling approach that if applied correctly can provide complete, efficient, understandable, and sustainable models (Geyer and Fourie 2015). Modelers have used BPMN to study information systems (Wohed et al. 2006), healthcare (Ojo 2012), and software development (Ballantine 2016). Modelers must carefully select model grammar to avoid user rejection of the model, due to some limitations of BPMN to reflect real world business rules (Recker et al. 2010). This constraint may limit the usefulness of applying BPMN to range decision-making due to its heavy use of real-world heuristics in defining decision processes.

b. Petri Nets

Petri Net Markup Language (Hillah et al. 1970; Desel and Reisig 2015) provides implementation for the Petri net process flow method. Petri nets are widely employed and have their own International Standard that ensures common usage (Hillah et al. 2009). Mehrez et al. (1995) demonstrated the viable use of Petri Nets for modeling behavioral processes and decision-making and showed how to make simple decision trees. The graphical visualization of the Petri net might be useful as an abstraction of the range event decision-making process. However, according to the NUWC Division, Keyport Range Manager, range managers and test planners do not receive training in modeling techniques or in using abstract methods to plan or conduct range events. These stakeholders, therefore, may not readily accept Petri nets modeling as a basis for evaluating their decisions.

c. Process Algebra

Process algebras such as Pi and Lambda Calculus can model concurrent communication threads (Wing 2002) which themselves are similar to behavior processes. Baeten and Weijland (1990) showed process algebra application to high-level modeling. Wang and Ruhe further state real-time process algebra (2009, 137) can model cognitive processes such as behaviors and sequences of actions.

Although a powerful tool, process algebras require proficiency in building notation and some understanding of programming. The goal of the thesis is to build a process model that range managers can use with minimal training. They generally have little software programming experience; therefore, the process algebra approach may be more complex than the problem requires.

d. Yet Another Workflow Language (YAWL)

The YAWL approach uses a tree-like hierarchical structure through connecting high-level Petri nets to simulate system processes, states, and transitions (YAWL 2016). YAWL can represent process flows similar to decision trees (van der Aalst and ter Hofstede 2005). Although YAWL has a relatively high level of abstraction, it is primarily graph oriented (Ouyang et al. 2006) whereas the range decision process is more akin to a block diagram approach. An abstract, graphical approach may not be suited to identifying high-value decisions in a format acceptable by acoustic range operators and planners.

e. Monterey Phoenix

Monterey Phoenix is a BPM approach that also provides high-level abstraction within a behavior-modeling framework (Farah-Stapleton and Auguston 2013). MP can model events, activities and sequences. Additionally, it is not constrained by the single flowchart template, which can lead to over-constrained process models. (Auguston et al. 2015). Use of Monterey Phoenix to model software architecture and other systems has been successful (Farah-Stapleton, Auguston, and Giammarco 2016). Monterey Phoenix is well suited for business process, system and software modeling, but to make it accessible to untrained range personnel would require more tutorials and educational materials than were available at the time of this writing.

f. Enhanced Functional Flow Block Diagrams

Enhanced Functional Flow Block Diagrams (EFFBD) build on traditional functional block diagrams by adding data flow overlays to provide accurate representation of data dependency (Long 2002). Long notes that EFFBD allows modelers to use either control or data triggers (or both) to initiate system functions, and provides status of trigger data queuing. EFFBDs provide descriptions of system functions and their execution order, and provide many constructs useful to modelers in representing processes (Seidner and Roux 2008). EFFBD tools such as CORE provide software that aids state transition mapping and behavioral modeling (Vitech 2016) and supports the construction of system models that can perform behavioral analysis (Rodano and Giammarco 2013). CORE supports multiple users and allows them to add and delete to the model through a centralized repository (Alghazzawe et al. 2014).

g. Action Diagrams

Action diagrams, activity diagrams or functional flow diagrams are methods of displaying action entities and their interactions with each other through input/output, resources, and logic flow constructs (SPEC Innovations 2017). These approaches originated with the development of the Unified Modeling Language (UML), which provided better representation of the development of software systems but have application to other business processes (Chen et al. 2007). As described by Chen et al., activity and action diagrams contain activity states that compute outputs based on their programming, and then pass their result on to the next activity state in the diagram. Many UML software packages provide multiple architecture views, models, examples, allocation and consumption of resources, and contains preloaded formats that match DOD Acquisition Framework views (Pospisal 2015). Action diagrams allow deconstruction/decomposition of more complex actions to better illustrate interactions between activities, functions, and tasks (SPEC 2016).

Action diagram software such as SPEC Innovation’s Innoslate tool provide model-based systems engineering tools that can manage requirements, model behaviors, and represent simple to complex processes (Rodano and Giammarco 2013). Innoslate also allows discrete event simulation (Ritter and Sperlazza 2016) which simplifies construction of a formal model that could represent the decision process used during a range test event.

2. Selection of Process Model Approach

All of the modeling approaches reviewed could potentially represent range decision processes. Each has sufficient grammar constructs to capture range test event details, and many have software applications available that allow simulation modeling. However, a primary goal of the thesis is to develop a model with a high chance of acceptance by range managers and operators who are untrained in formal modeling approaches or modeling software applications. According to the NUWC Division, Keyport Range Manager, these personnel use graphical approaches such as cause mapping, fault tree analysis, and block diagrams for both training and execution of range operations. Therefore, a process model that reflects these attributes would have a higher probability of adoption by range personnel. Modeling approaches that require high abstraction or knowledge of modeling theory would likely encounter resistance to adoption.

Action or activity diagrams are capable of representing decision processes used by range managers and ROs, and their usefulness in decomposing processes allows sufficient detail of the various decision activities encountered during range events. The simplified grammar available in action diagrams may also be useful in allowing untrained range operators to see and understand the functional flows of the model, which should increase the likelihood of the use of the model in assessing test event risk. Available software simulation applications provide sufficiently simple interfaces that range managers could use in their planning activities. Therefore, the thesis uses an action-diagram based approach for developing the formal model representing range event decision processes

B. SELECTION OF SIMULATION MODELING TOOL

This thesis uses Innoslate to provide a formal model of the acoustic range decision-making process. The author developed previous modeling architecture for the acoustic range using Innoslate, thus allowing the thesis to benefit from that work. Innoslate provides flexibility in representing behavioral processes and has a relatively simple user interface. Provided tools in the software allow for straightforward representation of decision points and other range behaviors, and previous work has shown a straightforward formal model of the range decision process is possible using the action diagram notation.

This chapter reviewed possible modeling approaches for application in describing the decision process of an acoustic range event. The review focused on decision models that could represent the decision process of the acoustic range test event. Examination of other process models was included to ensure consideration of a wide range of approaches. The review also highlighted factors that would contribute to adoption of a formal model. Since range managers and ROs would have little training in process modeling languages or abstract approaches, they would be more likely to accept activity diagrams with simple modeling grammar. The chapter concluded with the selection of the action diagram notation and modeling approach as implemented in the life cycle-modeling tool Innoslate for describing the acoustic range decision process.

III. ANALYSIS OF CURRENT TEST RANGE DECISION PROCESSES

The purpose of this chapter is to provide a description of the decision process used to control test events on the acoustic range and to provide a preliminary model to represent current knowledge about this process. The simple model describes a basic underwater test and uses a process flow chart to map the decision nodes, connections, and feedback loops to show the current state of decision-making. The chapter breaks this model down in an analysis of each step, providing observations on limitations of the current model and postulates possible high-value decision points based on the functions described.

A. ACOUSTIC RANGE MODEL CURRENT STATE

Levchuk et al. described heterarchical decision processes as those that are interdependent and may have a superior decision-maker based on abilities or the mission (2005). The acoustic range current decision process resembles a heterarchy due to the interdependence of the decision nodes and multiple actors in the process. According to the NUWC Division, Keyport Range Manager, acoustic range test events involve three phases: planning, execution, and analysis. He also provided the following synopsis of each phase of operations.

1. Test Event Planning Phase

In the planning phase, program personnel provide a test plan to identify test objectives, usually in the form of required data such as acoustic measurements, recording of three-dimensional real-time tracking of the unit under test (UUT), or other signals. Test directors (TD) use these test plans to develop a run plan, which provides specific instructions on setting up test equipment, position of launch and recovery craft, UUT settings, and timing of launches.

Both the RO and TD work together in the planning phase to develop the run plan. The TD ensures the run plan will achieve program objectives, which usually involves the collection of data. Examples of data collected include acoustic information such as UUT radiated noise, ambient noise from the environment, acoustic signals such as sonar, and tracking information. The TD designs the test sequence to maximize data collection in the time available for UUT run, usually limited by the test unit's fuel or power source. The TD usually produces a draft run plan and then provides the draft to the RO for review.

The role of the RO in test planning is to ensure the test will progress safely while achieving program objectives.

Risk mitigation decisions in the planning phase consist of establishing safety protocols to prevent the UUT from striking the firing ship, in-water sensors, or the seabed. TDs establish depth control and shutdown settings so that the UUT will return to its required depth band through software commands. If the UUT continues to operate outside the set depth band, shutdown settings will cause the unit to shut off its propulsion system and abort the run. TDs use the combination of launch position, launch heading, UUT speed, and the timing of course changes to develop run geometries that assist them in predicting where the UUT will be at any time during the test run. TDs use these geometries to manage safe ranges and positions of the launch vessel and test sensors as well as to prevent the UUT from hitting the seabed or shoreline. Use of this approach coupled with the high reliability of UUT control and shutdown safeties has resulted in no instances of a UUT striking a firing vessel in 50 years of operations.

2. Test Execution Phase

Once planning is complete, TDs provide the run plan to the range officer (RO) who uses the plan to develop various documents that provide specific instructions to technicians and range vessel operators. The documents communicate information such as which UUTs to launch and when, changes in setpoints from the original run plan, and any special instructions required by the RO to control the test. The RO issues these documents usually one to two days in advance of the test run date.

On the day of the test, the RO coordinates the actions of range vessels, support technicians, and other personnel to establish the proper initial conditions for testing. The RO uses a countdown type procedure (referred to as the countdown) to control the steps necessary to prepare the UUT for launch. The countdown has intentional stops or hold points built in such that the RO prohibits subsequent actions until all steps prior to the hold point are completed. Range operations personnel receive specific training and instruction on following countdown protocol to ensure this discipline. This approach provides the RO complete control over the progression of the test and ensures the UUT launch occurs only after all test parameters meet run plan specifications. The decision-making exercised by the RO in this phase consists of his evaluation of test preparations at each step of the countdown, and his assessment of readiness to proceed to the next step.

Once the RO decides preparations are complete, he gives the direction to launch the UUT. The RO then monitors the test run, observing for normal indications such as UUT following the predicted geometry, UUT speed, and depth. If the RO observes any abnormalities, the RO must choose from several options available. These options consist of allowing the test to continue with no action, directing the transmission or cessation of acoustic signals, or if the UUT is equipped with wire guidance, the shutdown of the UUT. These decision options reflect that not every abnormality requires UUT shutdown, as the result may simply be loss of one data parameter.

During test runs, the RO consults with the TD when possible to determine which option best meets program objectives. An RO's training requires them to take immediate action without consultation if in their opinion personnel, range vessels, test assets, or the UUT are in immediate danger of injury or damage. Such action may result in aborting the entire test run.

3. Analysis Phase

After UUT run, analysis teams receive data such as three-dimensional tracking recordings, acoustic measurements, and other signal recordings. The teams use this information to reconstruct the test run and determine whether the UUT performed as expected. If the teams determine UUT test run problems, they provide reports to program managers on possible root causes and recommended actions. These recommendations often result in adjustments to software, hardware, or procedural documents. If any problems are a result of mistakes made by range operations personnel, the teams provide this information to the range manager for corrective action.

B. TEST EVENT SIMPLIFIED MODEL

Figure 1 provides a simplified flow chart model of the decision process exercised by the range officer during the execution phase of the test event. The simplified model represents the basic elements of the current decision-making process used by the RO in controlling range events. As previously discussed, the model represents a notional event involving the launch of a self-powered high-speed test unit with a run time of approximately 15 minutes.

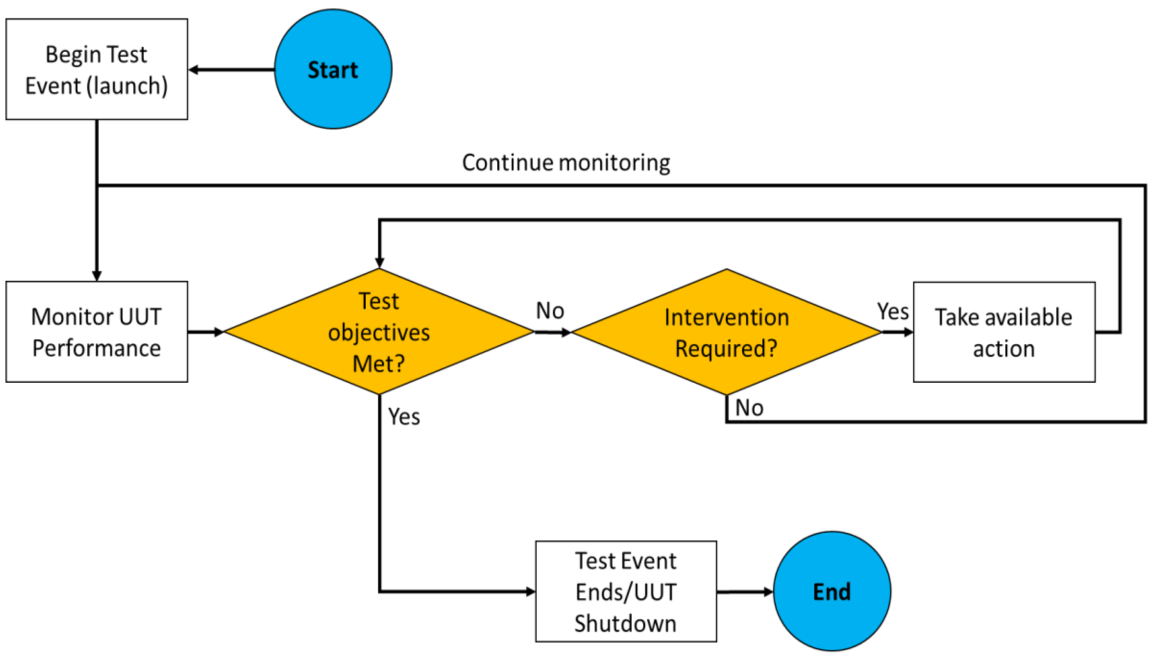

Figure 1. Range Event Flow Chart

1. Model Deconstruction

The scope of the thesis examines the decision processes used from the time of UUT launch until the end of the test run. As previously discussed, the test run ends either when the UUT runs out of fuel or receives a shutdown command ordered by the RO. The RO uses parameters such as UUT position on range, course, speed, depth, and acoustic signals generated by the UUT to decide if action is required. In these situations, the RO may choose to take no action. The following sections describe where decision points occur in the model.

a. Begin Event / UUT Launch

The model begins with the launch of the UUT after all launch preparations of made. The RO uses the countdown procedure to ensure all launch preparations such as UUT readiness, vessel heading and speed, and position of acoustic recorders and assets in their proper locations. Once the RO verifies these parameters are per the run plan, he gives the order to launch the UUT. The decision points include whether the UUT meets launch parameters, and whether range setup (vessels, weather) supports launch.

b. Monitor Performance

After UUT launch, the RO monitors indications to verify the UUT has started and is running as expected. Three-dimensional real-time track data is the primary indication used by the RO to monitor UUT run progress. Acoustic emanations from the UUT also provide indications of particular software routines in progress onboard the UUT, providing further information. This step of the process represents information gathering and so does not contain decision points.

c. Test Objectives Met

During this portion of the event, the RO compares UUT performance to the expected behavior provided in the run plan. Major milestones include the UUT changing course at preset coordinates, or changing course due to interaction with acoustic sources that stimulate UUT software actions. If the RO observes the UUT not acting per run plan expectations, he then moves to the next block. Decision points in this portion include determining if UUT performance, testing devices, vessels, or other factors are or remain sufficient for achieving test objectives and ensuring safety.

d. Intervention Required

Once the RO observes an abnormality, he must decide whether to intervene in the test or allow it to continue. The RO weighs the type of abnormality against the consequence of allowing it to continue. For example, a test may be evaluating the ability of the UUT to react to a specific sonar frequency. If the UUT fails to react, intervention may not be required since the test itself is evaluating that exact interaction. The test may provide multiple opportunities for such interaction, therefore, if the RO took action he would be interfering with testing objectives. If intervention is not required, the feedback loop shown represents the RO returning to monitoring the remainder of the event. This portion represents a high-value point in that if the RO decides that UUT or range safety is about to be compromised, he must take action that will likely end the test run prior to completion of all testing objectives.

e. Take Available Action

Once the RO decides action is required, he then must decide what action to take. Decision options include no action, adjustment of acoustic sources to stimulate UUT software actions, or directing a shutdown command (if the UUT is so equipped) that will abort the test. As test events are expensive, ROs generally do not shutdown UUTs unless in their opinion such action is necessary to protect personnel, range equipment or the UUT. For this reason, this block represents a critical decision point.

Once the RO takes action, he then evaluates if such action corrected the problem. The feedback loop to the Test Objectives Met block represents the RO's subsequent analysis of the effectiveness of his corrective action(s) and the decision process again enters the "Intervention Required" decision block.

f. Test Objectives Met: Yes

Once the RO observes that the event has achieved as many test objectives as possible, he can either allow the UUT to run to fuel exhaustion or command its shutdown. Depending on the type of test, a test objective may include UUT fuel exhaustion because as long as the UUT has fuel it continues to run. This requires the RO to continue monitoring to ensure range safety. The decision point in this portion centers on the RO determining if previous action was sufficient such that range safety and meeting test objectives is achievable.

g. Test Event Ends / UUT Shutdown

The event concludes when the RO determines that the test achieved all objectives or the UUT shuts down from fuel exhaustion or command shutdown. The RO has the option to allow the UUT to continue operations even if the test accomplished all requirements. According to the NUWC Division, Keyport Range Manager, ROs routinely allow the UUT to continue running even if equipped with command shutdown, as this allows program managers to have more data that may benefit test analysis.

2. Summary of Decision Points from the Simplified Model

- Intervention required. The RO determined overt action is required to protect the UUT from damage, ensure range safety, or prevent unnecessary loss of test data due to a change in test conditions or UUT performance
- Take appropriate action. The RO decides what action to take in order to protect the UUT or range assets or avoid loss of test data
- Test objectives met. The RO determines that all test objectives have been met and the test may conclude, either by the UUT running out of fuel or through a command shutdown of the UUT if so configured

3. Limitations of the Simplified Model

The simplified model is accurate but lacks the detail necessary to represent the decision process during a test event. The following paragraphs provide the improvements required in order to model the process adequately.

a. Lack of Representation of Launch Preparation Decisions

The simplified model decision process begins with the decision to launch based on completion of the countdown procedure. According to the NUWC Division, Keyport Range Manager, the RO must make other decisions prior to this point depending on UUT start up performance, range conditions such as vessel performance, launch system readiness, and weather. Many of these decisions can affect the outcome of the test event and therefore require representation in the model.

b. Influence of Range Environmental Conditions on Continuance of Testing

Weather, sea state, boating traffic, ambient noise, and marine mammal activity also influence the RO's decision to authorize UUT launch. The model lacks the granularity necessary to represent these decision factors.

c. Differences between Decision Types

The model does not distinguish between the decision to allow the test to continue after intervention (i.e., while test objectives remain) and the decision to end the event after accomplishment of required test objectives. These decisions are of significant difference to warrant separate representation.

d. Possible Outcomes of Taking Action

The model assumes that if the RO takes action, the resulting sub-process is the determination whether the event is meeting test objectives. However, the RO may need to take action that will immediately end the event due to safety or other concerns. The model does not reflect this possible decision outcome.

This chapter analyzed a preliminary process flow chart that described current knowledge about a basic underwater test event at the acoustic range. The chapter identified existing critical decision points represented in the model and the purpose of these decisions. The chapter concluded with an analysis of limitations of the simplified model in order to influence a more accurate representation in the subsequent formal model.

4. Simplified Model Validation

Review of the simplified model with the NUWC Division, Keyport Range Manager confirmed it represented the basic elements of the range decision process.

IV. CONSTRUCTION OF A FORMALIZED TEST RANGE MODEL

This chapter provides a formal model of the preliminary process model presented in Chapter II using the Innoslate software application. This formal model captures the Chapter II analysis recommendations for improving the precision and completeness of the decision flow process for the subject acoustic range test event. The formal model describes and includes additional decision nodes, which expands the set of possible decision flows for consideration in advance of an actual test event. The chapter also provides a discussion of the modeling framework and construction of the model as well as results of several modeling runs. The chapter concludes with observations on the model run results and possible implications for actual acoustic test range events.

The model uses generic language to describe decisions, choices, and consequences of the choices. For example, a decision point preceded by "take available action," followed by the decision point labeled "action effective?" followed by outcomes of yes or no. This allows the model to use a simplified construct for evaluating the decision process that also is generic enough to represent any yes/no decision type. Labeling the consequences of each outcome so that the user understands the implications of each decision choice allows users to understand these simple decisions in their own specific vernacular. This approach allowed for a reasonable expedient construction of model flow regardless of the type of mission supported. Limiting the initial modeling to yes/no decisions also aided in identifying clear consequences of actions so that users had less trouble in visualizing the decision flow.

A. IMPROVEMENTS TO THE SIMPLIFIED MODEL

The simplified model has several weaknesses that require improvement to describe accurately the test-event decision process. Table 1 below outlines modifications required. Locations correspond to the points shown in Figure 2.

Table 1. Simplified Model Improvements

Modification	Reasoning	Figure 2 Position
UUT preparation supports launch	Reflects verification of necessary UUT initial conditions	1
Range setup	Data recorders, vessels, weather, ambient noise conditions must all meet set parameters prior to launch	2
UUT performance as expected	Current decision point (Test Objectives Met) focuses on test objectives only, and does not reflect other factors such as UUT malfunction which may require RO decision/action	3
Test run completion decision block	Simplified model does not distinguish between test objectives occurring during the event (i.e., test event milestones) and completion of the test. A separate feedback loop is needed to continue the test if objectives are not met versus deciding if all objectives are met.	4
Test abort	The RO requires the ability to abort the test at any time due to UUT problems or range safety issues	5

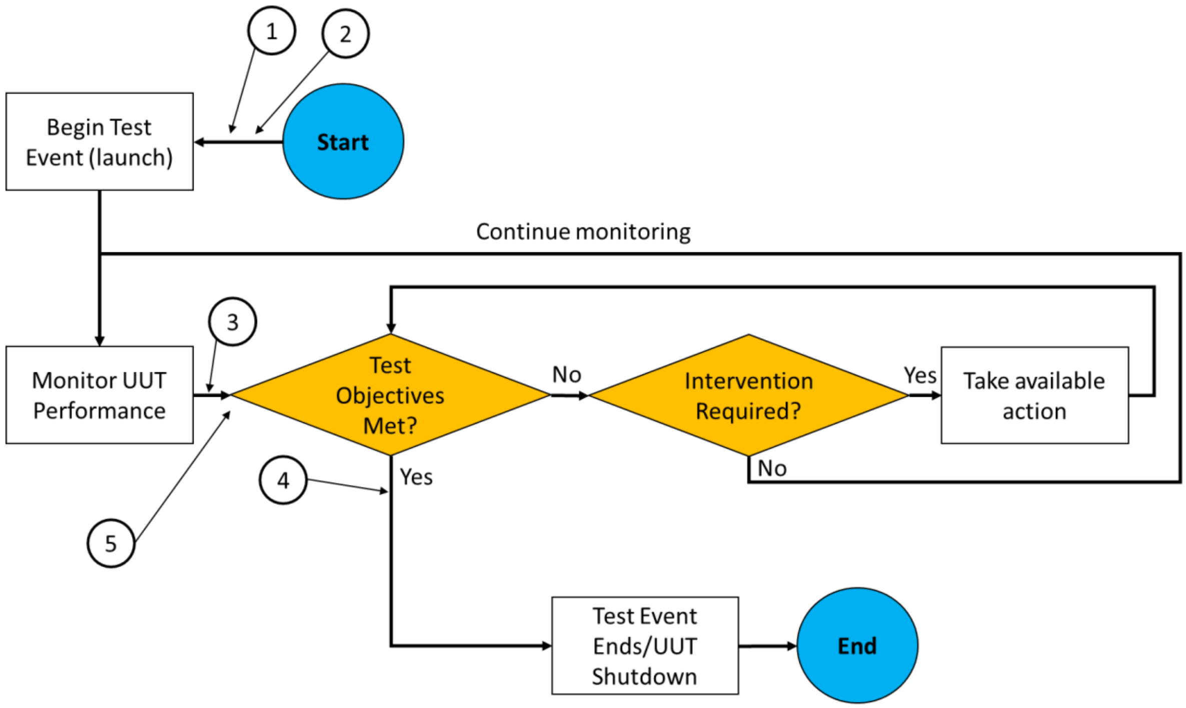

Figure 2. Simplified Model Corrections

B. MODEL ASSUMPTIONS

The formalized model assumes the following initial conditions and test parameters exist prior to simulation runs.

- The RO has access to all information necessary to make decisions. Situations where needed information is unavailable or in error are not modeled in this version.
- The RO has the requisite training to recognize each decision point.
- The RO is aware of possible decision choices at each point, including the no-action alternative.
- The RO is aware of only the information available at the time of the decision, i.e., the model does not allow for hindsight.
- The RO makes decisions at each point only once and does not alter these decisions unless allowed by the model construct.
- UUT performance follows historical experience, i.e., the model does not introduce previously unknown behaviors.

C. FORMAL MODEL FRAMEWORK

The thesis establishes the formal model framework by beginning with the simplified model and adding improvements necessary to capture the major decision elements in a typical acoustic test range event. The formal model uses the Innoslate software tool to replicate decision points, necessary resources for those decisions, feedback loops, and inputs/outputs. The following life cycle modeling language (LML) constructs available in Innoslate are used:

- **Action blocks** represent the various functions in the model. They allow the model to set initial conditions and outcomes for decisions blocks (OR functions). They can also be set to provide criteria for entering and exiting LOOP functions through use of script in the Innoslate tool. Action blocks provide a method for describing the consequences of outcomes from decision blocks, and are therefore useful in assisting users of the model to understand the result of decision choices.

- **LOOP functions** are action blocks that provide a recursive activity that repeats a series of imbedded actions until conditions meet an exit criterion. Script in Innoslate can be set to monitor each action block within the loop for various criteria, which can be set to either continue or exit the loop. The formal model construct uses basic true/false values in these action blocks to determine if the loop will end or continue running, depending on the outcome of imbedded OR decision points.

- **OR blocks** are another type of action block that provide decision functions within the formal model. Script can be set so that either a probability function, the presence of an input (resource), or a customized set of conditions determine the decision outcome. To avoid an unnecessarily complex model, OR outcomes in the formal model were limited to simple yes/no criteria with probability values assigned to each outcome. During simulation runs, Innoslate uses a random number generator function to determine a value within a normal probability distribution and then compares that value to the yes/no probability values set for that OR block.

D. MODEL CONSTRUCTION

1. Replication of the Simplified Model

Figure 3 shows the simplified model constructed in the Innoslate tool. As described in section B of this chapter, Figure 3 differs from Figure 1 due to the simplified model decision point of Test Objectives Met did not distinguish between individual test objective issues and overall test objectives.

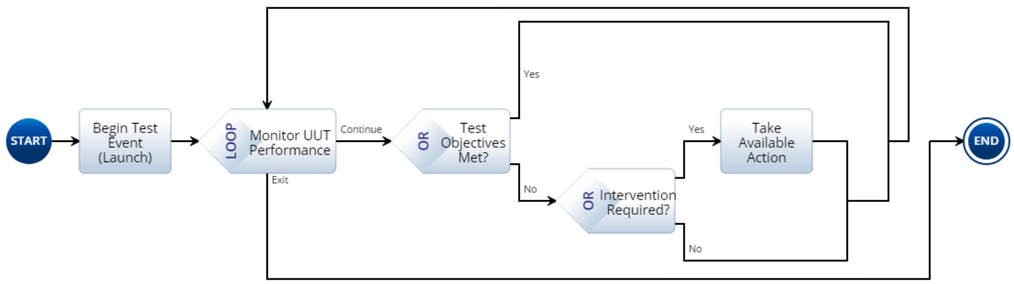

Figure 3. Simplified Model in Innoslate

To allow the model to function in simulation, the Monitor UUT Performance block contains the exit criteria for the overall test (test completion). As discussed previously, Innoslate provides simple programming language to assign time durations, probabilities, loop exit conditions, and test abort criteria. These features allow for necessary modifications to the simplified model to provide a closer representation of the actual decision process used by the RO during an acoustic test event.

2. Model Improvements

Figures 4 and 5 demonstrate the improvements made to the simplified model so that it more closely represents the current decision process used for acoustic events. Figure 4 shows the addition of a node to verify initial conditions. Per Table 1, the RO must evaluate several environmental and technical conditions prior to allowing launch. For example, weather and sea states must support not only the launch of the UUT but also the ability to retrieve the UUT once its powered run is complete. Technical conditions such as UUT warm up, entry of launch system parameters, and startup of data recording systems must be established and verified. The decision to proceed with UUT launch has high value because failure to set proper conditions can result in an aborted test or loss of valuable data.

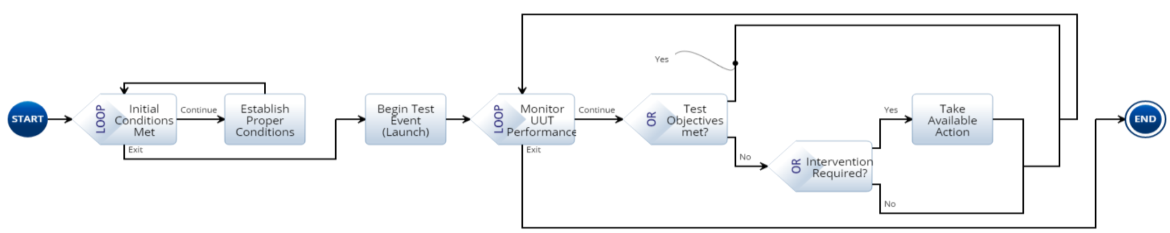

Figure 4. Addition of Initial Conditions Decision Block

Figure 5 expands and modifies the Initial Conditions Met section to represent more accurately the actual decision made by the RO at this point in the test. The simplified model did not adequately illustrate the recursive decisions the RO encounters during range and UUT preparations. The decision node as modeled provides for a more accurate simulation of the duration of this portion of the test.

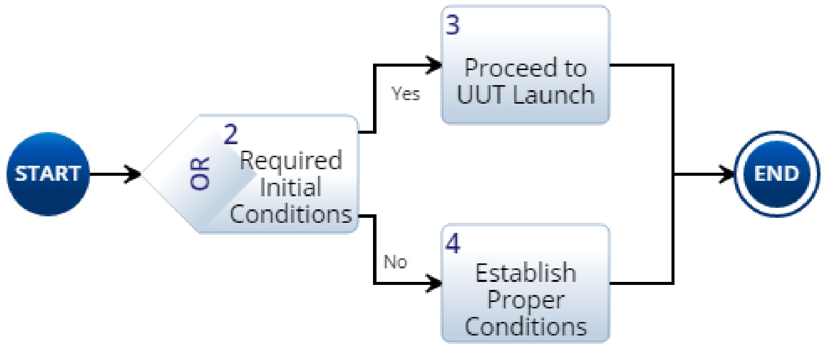

Figure 5. Consolidation of Initial Conditions Decision

Figure 6 shows the addition of a decision point to Figure 4 that requires the RO to decide if the UUT is performing per expectations (oval). If during the test run the UUT malfunctions or behaves in an unexpected way, the RO may be required to take actions ranging from altering the UUT run to aborting the test. Inputs to this decision include environmental factors such as weather and ambient noise, as well as UUT performance parameters such as speed, depth, course, and course change sequences. This addition address the weakness identified as point 3 in Figure 2.

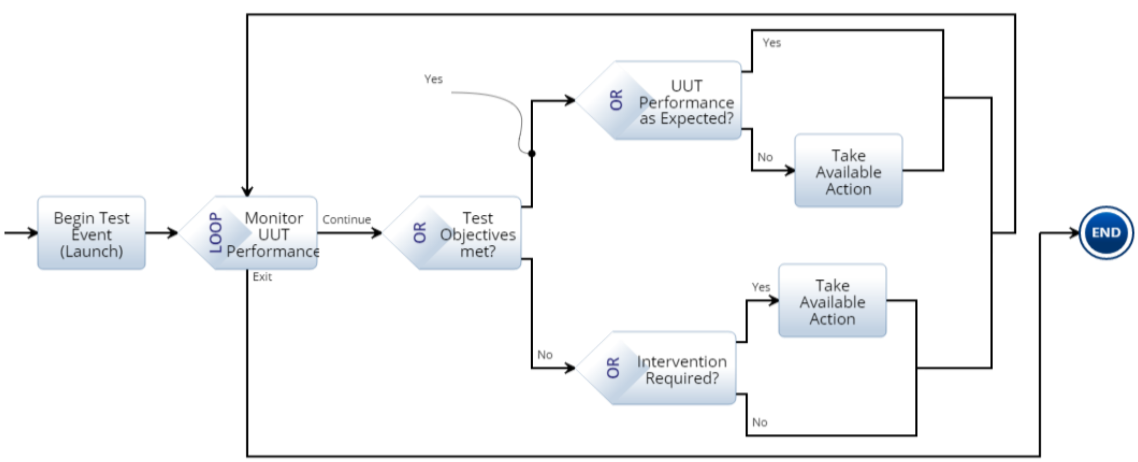

Figure 6. Unit under Test Performance

Figure 7 shows further modification of the Monitor UUT Performance section that now contains the criteria for exiting the Monitor Performance loop. The added language (arrow) defines that the loop continues until all test sequences objectives are accomplished. The following OR block is also modified to reflect monitoring of test sequence objectives, to avoid confusion with monitoring for overall test completion (now accomplished in the preceding block). This modification addresses the problem identified as point 4 in Figure 2.

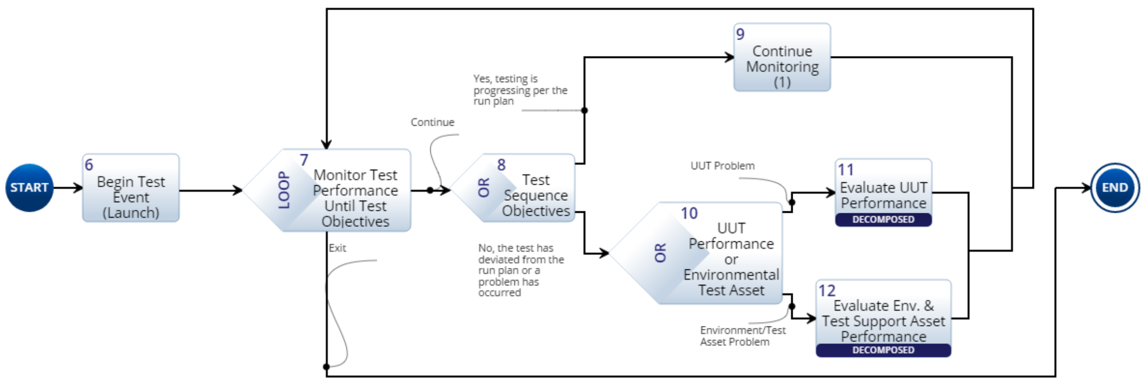

Figure 7. Distinguishing between Test Sequencing and Test Completion

Following the Test Sequence Objectives Met OR block, the adding of additional branches distinguishes between UUT problems and test asset/environmental issues that could interfere with proper test sequencing (see oval). Decomposition of each branch appears below.

The addition of Block ID numbers to each block aids in referencing during construction and analysis. The Continue Monitoring Block now shows a number in parenthesis to distinguish this block from other blocks in the model with the same function. The model repeats this convention for other similar block labels. Additionally, Innoslate assigns each block its own unique ID number, which assists in tracking how the model executes the various branches.

Figure 8 shows the decomposition of the Evaluate UUT Performance branch. OR nodes represent the decision points encountered by the RO if UUT issues arise during the test, and the subsequent actions for these decisions. Scripts in the OR and Action blocks allow the model to progress to the next state depending on decision outcomes. Descriptions of the decision options added to the branches describe the decision options open to the RO at each node. Action blocks now contain unique identifiers for ease of cross-referencing.

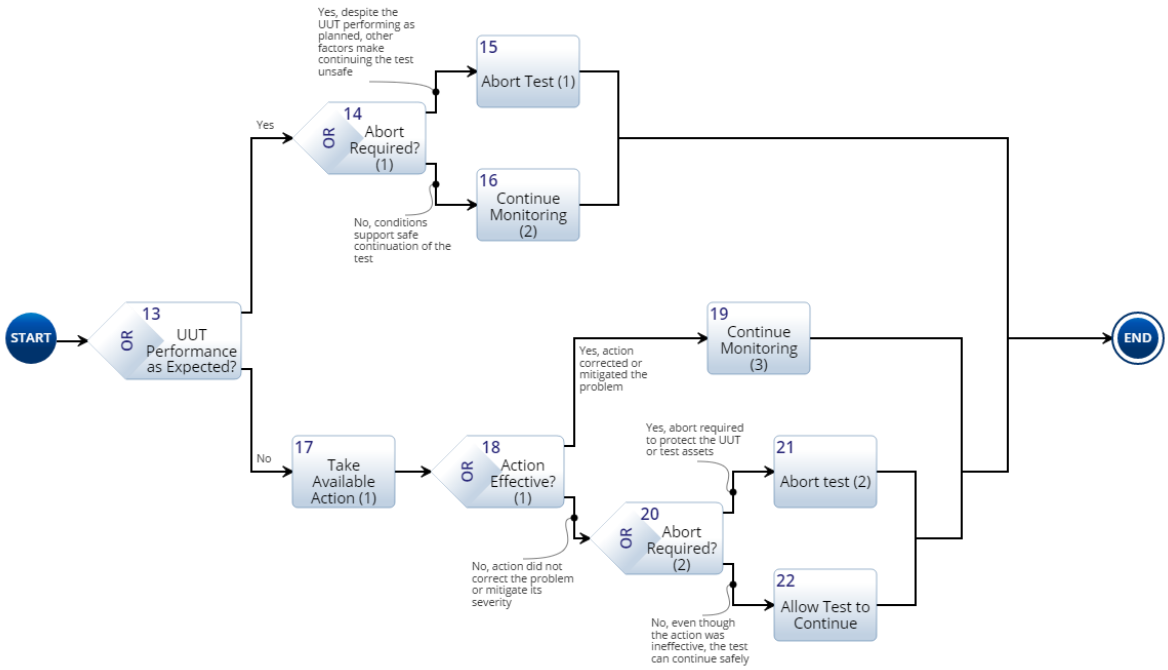

Figure 8. Evaluate UUT Performance Branch

Figure 9 shows the decomposition of the Problem with Environment or Test Support Assets branch. Similar to Figure 8, test abort functions or the continuance of monitoring are now provided as decision outcomes. Branch description language identifies the options open to the RO.

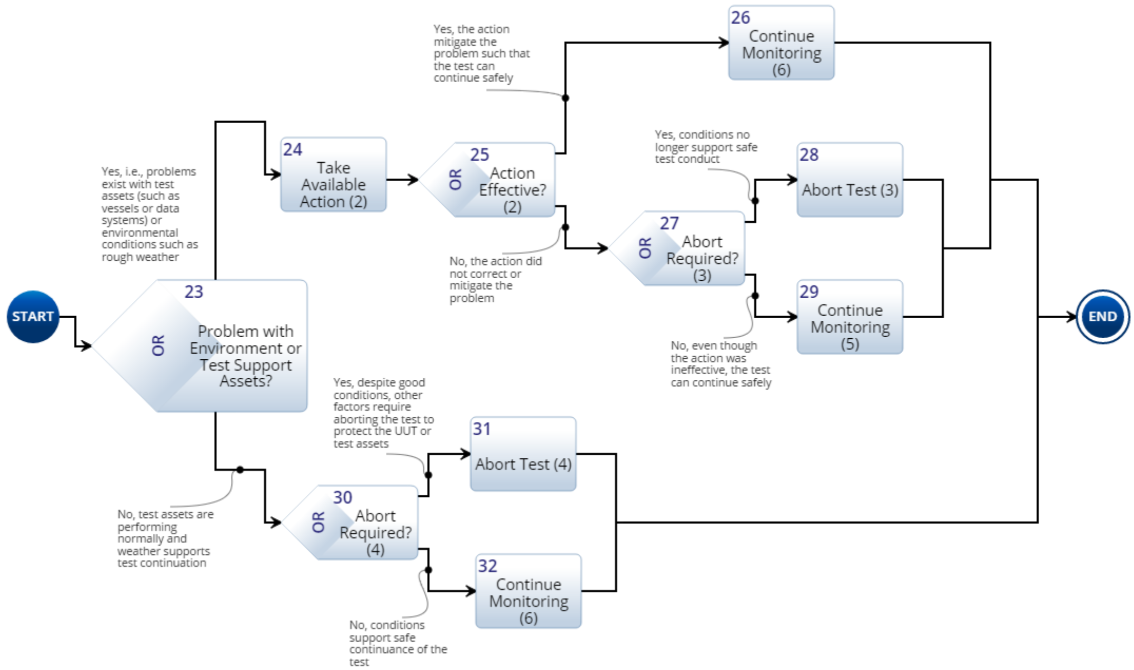

Figure 9. Evaluation of Test Asset/Environment

The additional language and branches in Figures 8 and 9 now provide the test abort capability required by the RO, and address the problem noted in point 5 of Figure 2.

Figure 10 shows a consolidation of the two main sections of the formal model. Adding this layer allows for the use of the decomposition function offered in Innoslate, and enables more intuitive use and exploration of the model by potential users. The Verify Initial Conditions block decomposes to the actions described in Figure 5; Conduct Test decomposes to the actions in Figure 7 with subsequent decompositions shown in Figures 8 and 9.

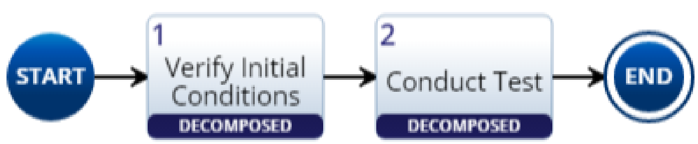

Figure 10. Model Consolidation

E. MODELING RUNS

Once the model was constructed and debugged, parameters were chosen for the various probabilities and durations found in each of the decision nodes and action blocks. These parameters were determined through interviews and walk-throughs with ROs who conduct test events on the acoustic range in order to obtain a reasonable baseline of values. For ease of reference, Appendix A to the thesis contains block ID designations, Innoslate simulation block identifiers, block labels, and descriptions of the functions of each block. The appendix also contains the initial probability and duration settings for each action, LOOP, and OR block in the formal model.

1. Model Run Setup

Innoslate provides a Monte Carlo simulation function that allows the formal model to execute multiple runs to provide statistical results of the decision flows. The model used one thousand iterations per run to achieve a reasonable level of fidelity in the results and to observe trends. Innoslate provides options for determining the outcome of OR decision blocks by setting discrete probabilities for the yes/no choices, or to select a probability function such as normal, uniform, or other common distributions. For ease of model set up and straightforward comparison of decision block usage, the model used discrete values recorded in Appendix A.

2. Model Baseline Runs

Using the baseline setpoints for the model found in Appendix A, the model executed 10,000 simulation runs in 1,000-run increments. Innoslate generated spreadsheets for each run that provided data on the frequency each action block was active during an individual run. Table 2 provides the summary of baseline run data for all blocks in the formal model.

Table 2. Frequency of Action Block Usage during Baseline Model Runs

Block ID	Action Block Label	Frequency										
		1	2	3	4	5	6	7	8	9	10	Average
1	Verify Initial Conditions	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
2	Required Initial Conditions Met?	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
3	Proceed to UUT Launch	105	100	111	98	111	108	92	94	108	91	101.8
4	Establish Proper Conditions	895	900	889	902	889	892	908	906	892	909	898.2
5	Conduct Test	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
6	Begin Test Event (Launch)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
7	Monitor Test Performance Until Test Objectives Complete	1963	1848	1859	1910	1895	1875	1930	1887	1930	1906	1900.3
8	Test Sequence Objectives Met?	963	848	859	910	895	875	930	887	930	906	900.3
9	Continue Monitoring (1)	759	669	693	728	714	702	752	702	742	715	717.6
10	UUT Performance or Environmental Test Asset Problem?	204	179	166	182	181	173	178	185	188	191	182.7
11	Evaluate UUT Performance	83	76	57	68	81	64	57	66	69	87	70.8
12	Evaluate Env. & Test Support Asset Performance	121	103	109	114	100	109	121	119	119	104	111.9
13	UUT Performance as Expected?	83	76	57	68	81	64	57	66	69	87	70.8
14	Abort Required? (1)	73	68	52	60	71	56	54	60	63	78	63.5
15	Abort Test (1)	7	3	5	3	4	5	5	6	2	4	4.4
16	Continue Monitoring (2)	66	65	47	57	67	51	49	54	61	74	59.1
17	Take Available Action (1)	0	8	5	8	10	8	3	6	6	9	6.3
18	Action Effective? (1)	0	8	5	8	10	8	3	6	6	9	6.3
19	Abort Required? (4)	10	10	10	12	10	3	17	16	14	8	11
19	Continue Monitoring (3)	1	1	1	1	2	0	1	2	0	3	1.2
20	Abort Required? (2)	9	7	4	7	8	8	2	4	6	6	6.1
21	Abort Test (2)	1	2	2	0	2	1	1	0	0	1	1
22	Allow Test to Continue	8	5	2	7	6	7	1	4	6	5	5.1
23	Problem with Environment or Test Support Assets?	121	103	109	114	100	109	121	119	119	104	111.9
24	Take Available Action (2)	0	93	99	102	90	106	104	103	105	96	89.8
25	Action Effective? (2)	0	93	99	102	90	106	104	103	105	96	89.8
26	Continue Monitoring (4)	65	59	65	68	48	65	56	59	61	55	60.1
27	Abort Required? (3)	46	34	34	34	42	41	48	44	44	41	40.8
28	Abort Test (3)	5	2	4	0	3	5	4	5	4	6	3.8
29	Continue Monitoring (5)	41	32	30	34	39	36	44	39	40	35	37
31	Abort Test (4)	1	1	2	1	1	0	1	2	2	0	1.1
32	Continue Monitoring (6)	9	9	8	11	9	3	16	14	12	8	9.9

Table 2 shows that not all simulation runs resulted in the use of all action blocks. Performance of multiple sets of runs revealed that all decision and action blocks are active at various times. This showed that all model paths and branches are active and are possible outcomes. Table 3 provides information on the frequency of appearance of decision blocks only.

Table 3. Action Block Frequency during Baseline Runs

FREQUENCY OF DECISION BLOCK APPEARANCE DURING BASELINE RUNS							
Block ID	**Innoslate ID**	**Block Label**	**Previous Block**	**Activity**	**Function**	**Description**	**Frequency of Appearance**
2	e20PA1	Required Initial Conditions Met?	1	OR	Decision node	RO verification that initial conditions support UUT launch	1000
8	e3WGC2	Test Sequence Objectives Met?	7	OR	Decision node	RO verification that the test is progressing per the run plan	900.3
10	e3XQE1	UUT Performance or Environmental/Test Asset Problem?	8	OR	Action if outcome to 8 is NO	RO decision on whether problem is UUT or Environment/Test Asset related	182.7
13	e3WT4H	UUT Performance as Expected?	11	OR	Decision node	RO decision on whether UUT performance is as expected based on the run plan and RO experience	70.8
14	e5T511	Abort Required? (1)	13	OR	Action if outcome of 13 is YES	If the RO observes a problem but the UUT is performing normally, he must decide if a test abort is required regardless	63.5
18	e6RBTH	Action Effective? (1)	17	OR	Decision node	RO evaluation of corrective action effectiveness	6.3
20	e5SHG2	Abort Required? (2)	18	OR	Action if outcome of 18 is NO	If action taken is ineffective, RO must decide if test should continue	1.2
23	e5SHG1	Problem with Environment or Test Support Assets?	12	OR	Decision node	RO decides if test assets or environment (e.g. weather, sea state) are a problem	5.1
25	e2QWH	Action Effective? (2)	24	OR	Decision node	RO evaluation of corrective action effectiveness	89.8
27	e8KJBJ	Abort Required? (3)	25	OR	Action if outcome of 25 is NO	If action taken is ineffective, RO must decide if test should continue	60.1
30	e21KKH	Abort Required? (4)	23	OR	Action if outcome of 23 is NO	If action taken is ineffective, RO must decide if test should continue	37

3. Sensitivity Analysis

The thesis research question centers on the ability of a formal model to identify high-value decision points in a decision process. To assist in determining if the formal model can provide this insight, Appendix B documents probability adjustments made to two decision blocks within the "Problem with Environment or Test Support Assets?" branch. Block 25, "Action Effective (2)" yes/no values were changed from 60/40 to 40/60, and Block 27 "Abort Required (5)" yes/no values changed from 10/90 to 30/70. Alterations were limited to this branch only to simplify observing changes in model execution as decision parameters were changed. The model executed 10,000 runs with results provided in Table 4.

The purpose of these changes was to verify model design would respond as expected given simple changes to the decision parameters. Further model refinement would include quantitative analysis of downstream effects of changes in decision durations and probability values.

Table 4. Quantitative Analysis Showing Sensitivity of Decision Frequency to Decision Probabilities

Block ID	Block Label	Frequency Averages After Changes	Baseline Average (From Appendix B)	% Change
2	Required Initial Conditions Met?	1000	1000	0.0%
8	Test Sequence Objectives Met?	895.3	900.3	0.6%
10	UUT Performance or Environmental Test Asset Problem?	179.3	182.7	1.9%
13	UUT Performance as Expected?	72.5	70.8	2.4%
14	Abort Required? (1)	64.7	63.5	1.9%
18	Action Effective? (1)	7.8	6.3	23.8%
20	Abort Required? (2)	5.5	1.2	358.3%
23	Problem with Environment or Test Support Assets?	106.8	5.1	1994.1%
25	Action Effective? (2)	97.2	89.8	8.2%
27	Abort Required? (3)	59.5	60.1	1.0%
30	Abort Required? (4)	9.6	37	74.1%

Table 4 shows the results of making the changes indicated in Appendix B. Probability values of OR blocks 25 and 27 were the only changes made to the model. As Table 4 indicates, the frequency values for these blocks changed little, but other decision blocks experienced large changes in their frequency of appearance, especially 18, 20, 23 and 30.

This chapter introduced a formalized model used to represent a simplified test event on the acoustic range. Discussion of assumptions, framework, parameters, and construction explained how the model represents a range event in terms of the decision flow used to control the test. Description of the stages of model construction displayed modifications of the simplified model that result in formulation of a formal model using the Innoslate simulation tool. Results of modeling runs provided data useful in determining the model's effectiveness at representing process flows and decision nodes during a test run. The chapter concluded with a limited sensitivity analysis that showed how adjustments to model decision probabilities resulted in changes to the frequency in which the model used specific decision points.

4. Model Validation

As with the simplified model, the NUWC Division, Keyport range management reviewed the formalized model and confirmed it adequately represented a routine test event. They provided several improvement recommendations for further study that would assist the range in better test planning. These recommendations are included in the following chapter.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The purpose of this chapter is to provide conclusions regarding the research question postulated in this thesis, in light of the analyses presented earlier. The chapter provides findings, resolves the thesis question, and offers recommendations for model use and further research that may assist NUWC Keyport range personnel and those working in other T&E domains. The chapter concludes with recommendations for further study.

A. FINDINGS

Findings focus on the ability of the formal model to represent a simple range event, the ability of the model to predict high-value decision points, and the usefulness of the formal model as potential tool to range managers.

1. Modeling of a Routine Range Event

Improvements to the simplified model resulted in a formal model that better described the actual decision process used during test events. This also allowed easier replication of the process when building the model in Innoslate. The following paragraphs describe specific comparisons of the two models.

a. Logical Flow of Events

The simplified model discussed in Chapter IV provided a starting point for analysis of the range decision process. The model provided a basic flow of the decision process followed by a RO during a test event, but lacked the detail to represent several key decision points such as verification of initial conditions and determination of UUT and test asset performance. The formal model improved on this flow to represent the actual range-event decision process.

b. Decision Probabilities

The simplified model had no ability to represent the likelihood of the RO's decision in any situation. The use of the Innoslate tool provided the formal model with the flexibility to represent discrete yes/no probabilities, which in turn allowed for Monte Carlo simulation of possible decision flows. This was not possible with the simplified model.

c. Frequency of Decision Block Appearance

The simplified model discussed in Chapter IV contained two decision points as compared to the formal model, which has eleven. As discussed in Chapter V, these additions were necessary to account for the various decisions the RO actually makes during a test event.. These additions allowed the model to represent more closely the multiple decision paths experienced by the RO during testing.

d. Allowance for Aborting the Test

As discussed in Chapter V, the simplified model provided no option to represent the RO decision of aborting the test due to technical or safety concerns. The formal model provides four separate abort decision blocks that represent the possible actions required if the UUT, test assets, or the physical environment pose unacceptable risks.

2. Identification of High-Value Decision Points

Chapter IV showed the frequency in which each action, loop, and decision block was active during each of the run increments, and the average for all runs. Range managers can conclude that because ROs encounter these decisions often, they have a high probability of affecting successful test outcome and therefore a high value. These insights can assist range managers in the following areas:

- determining which decisions warrant focused or additional training when qualifying range officers, because ROs will encounter these decisions often
- applying resources for additional risk management in the decision area, since reducing the risk of an incorrect decision will reduce risk of prematurely aborting or adversely affecting a test run

- improving range data or situational awareness tools so that ROs can make better and more informed decisions in the critical area

- comparing the high-value decision location in the test sequence to the probability of UUT vulnerability. At certain intervals during the test, a UUT may be more vulnerable to a poor decision than during other portions of the test. Advance knowledge that such vulnerability coincides with a high-value decision would allow managers to better prepare for the test run and apply necessary mitigations.

- determining personnel assignments. Managers could analyze and upcoming test and realize the risk of incorrect decision-making is high, and from that determination assign a more experienced or seasoned RO to minimize the risk of an improper or unwarranted decision.

3. Usefulness of the Model to Range Managers

Thesis assumptions, research, development of the formal model, and model run results were included in a brief provided to NUWC Division, Keyport range managers and subject matter experts. Examples presented were:

- ability to represent key decisions

- ability to set probabilities for decision nodes

- formal model data products showing frequency of various decision types

- ability to conduct pre-event planning through Innoslate by modifying the model for different or new types of range events

- capability for analyzing decision points and flow paths through Monte Carlo simulation

- possibility of pre-event risk analysis

- use of the model as a quantitative risk management tool

Range experts concluded the model has application to their range planning process. Discussion centered on how model refinements, especially quantitative analysis to generate accurate decision probabilities, could greatly improve the model's predictive accuracy and usefulness in range planning. Range managers commented the tool had application to their decision processes and that the model provided a method of analyzing the conduct of current and potential range events.

B. RESOLUTION OF THE THESIS RESEARCH QUESTION

The thesis posed the question, can formally modeling the business process of conducting test range events expose previously overlooked ambiguities and high-value decision points? The formal model provided accurate representations of the choices facing the RO, as well as providing a means to evaluate the relative worth of those decisions. Use of the Innoslate software revealed high frequency decision nodes, which NUWC range managers concluded were high value decisions. Thus, the formal model provides a pre-event risk analysis tool that range managers can use in both improving existing types of range events and planning for first-time events testing new systems. Therefore, use of a formal model representing a range test event does expose ambiguities and illuminates high-value decision points in that process.

C. RECOMMENDATIONS

The following recommendations resulted from the research conducted and lessons learned from the formal modeling runs.

1. Continue Model Improvements

The thesis based the formal model on a simplified test range event. Range managers can immediately improve on the model by mapping out a more accurate decision flow for different types of events to improve accuracy. Likewise, observations of test events and discussions with ROs and other subject matter experts may reveal other decision points or processes that could improve model accuracy. Additional recommended improvements include:

- Determine if an abort option is required for the Initial Conditions Met decision loop.. This was not included in the formal model as the focus was on RO decisions after UUT launch. For example, range managers may want to use the model to explore probabilities of test scrubs due to weather problems, and could use this information to inform potential customers of the schedule risks if they choose rough weather months for testing.
- Use data collection techniques to observe actual decisions and outcomes to improve the accuracy of probabilities assigned to the formal model decision points. As discussed in Chapter V, higher accuracy in the

decision probabilities will lead to a more accurate and predictive formal model.

2. Use as a Risk Management Tool

The thesis showed the formal model has the flexibility to represent not only existing events but also could be modified to represent future events or potential improvements to current test practices. For example:

- Range managers can apply heuristic experience from similar test events to modify the formal model to represent untried events, and thus provide quantitative, pre-event risk analysis. By using risk management tools such as event trees (Ferdous et al. 2011) and risk matrices (DAU 2017), managers can identify potential issues by using simulation rather than waiting for problems and then applying corrective actions after the fact. The range does not currently use predictive modeling for risk analysis in any fashion for new range events.

- Range managers can also exploit the visual nature of the formal model to identify more desirable and lower-risk decision branches and then determine the probabilities necessary in key decision blocks to accomplish those paths. Managers could then apply mitigation strategies to achieve those probabilities, thus influencing the decision process towards lower risk.

D. FURTHER STUDY

1. Future Use as of the Model as an Acoustic Test Range Planning Tool

As previously discussed, the formal model represented a simplified generic test event. Further research is required to improve the accuracy of the model in representing an event involving a specific type of UUT. The author recommends further analysis to determine whether the model is sufficiently accurate to replicate an actual test event.

2. Possible Use of the Model for Other Types of Test Ranges

The thesis showed the formal model in generic terms to illustrate that the approach and syntax of model construction apply to many types of decision processes. By keeping decision-points limited to yes/no choices, complicated test processes received sufficient detail so that a simplified test event process was recognizable. Therefore, this modeling approach is not limited to acoustic testing alone and has application to other types of test ranges, and has application to any decision process capable of simplification to a yes/no decision flow. While this limitation does not support all decision processes, findings listed in this thesis indicate useful analysis and insight are possible with the formal model approach.

APPENDIX A. FORMAL MODEL BLOCK IDENTIFICATION, TIMING, PROBABILITY VALUES

This appendix provides details used to define and set parameters used to populate the formal model activity blocks in Innoslate.

FORMAL MODEL BLOCK IDENTIFICATION & PARAMETERS

Block ID	Innoslate ID	Block Label	Previous Block	Activity	Function	Description	Duration (Minutes)	Script	Probability Values (%)	
									Yes	No
1	e7N1SH	Verify Initial Conditions	None	Action	Represent overall activity of establishing necessary conditions for test	Provides duration for test event preparations	360	None	N/A	N/A
2	e20PA1	Required Initial Conditions Met?	1	OR	Decision node	RO verification that initial conditions support UUT launch	30	Probability	10	90
3	e3N61	Proceed to UUT launch	2	Action	Action if outcome to 2 is YES	Account for time necessary to provide directions to launch UUT	20	None	N/A	N/A
4	e6QR9J	Establish Proper Conditions	2	Action	Action if outcome to 2 is NO	Account for time necessary to provide directions to launch UUT	60	None	N/A	N/A
5	e7N1SJ	Conduct Test	1	Action	Overall activity for test conduct	Decomposes to various activities that represent test conduct	60	None	N/A	N/A
6	e8KW41	Begin Test Event (Launch)	5	Action	Provide starting action	Specific action in the formal model to represent test event start	5	None	N/A	N/A
7	e20CHH	Monitor Test Performance Until Test Objectives Complete	6	LOOP	Allow recursive monitoring of test sequencing	Allows model to represent RO's monitoring to the test event as the test sequence occurs	30	Continues until encountering a FALSE value	N/A	N/A
8	e3WGC2	Test Sequence Objectives Met?	7	OR	Decision node	RO verification that the test is progressing per the run plan	2	Probability	20	80
9	e8M5WH	Continue Monitoring (1)	8	Action	Action if outcome to 8 is YES	Represents duration of monitoring while test is progressing normally	3	None	N/A	N/A
10	e3XQE1	UUT Performance or Environmental/Test Asset Problem?	8	OR	Action if outcome to 8 is NO	RO decision on whether problem is UUT or Environment/Test Asset related	5	Probability	40	60
11	e7NBJ1	Evaluate UUT Performance	10	Action	Action if outcome of 10 is "UUT Problem"	Decomposes to activities supporting evaluation of UUT performance	5	None	N/A	N/A
12	e11J71	Evaluate Env. & Test Support Asset Performance	10	Action	Action if outcome of 10 is "Environment/Test Asset Problem"	Decomposes to activities supporting evaluation of Environmental/Test Support Asset performance	5	None	N/A	N/A
13	e3WT4H	UUT Performance as Expected?	11	OR	Decision node	RO decision on whether UUT performance is as expected based on the run plan and RO experience	1	Probability	90	10
14	e5T511	Abort Required? (1)	13	OR	Action if outcome of 13 is YES	If the RO observes a problem but the UUT is performing normally, he must decide if a test abort is required regardless	1	Probability	5	95
15	e11VZH	Abort Test (1)	14	Action	Action if outcome of 14 is YES	Captures duration if RO aborts test	3	None	N/A	N/A
16	e2274H	Continue Monitoring (2)	14	Action	Action if outcome of 14 is NO	Captures duration if RO continues test	3	None	N/A	N/A
17	e3X3X1	Take Available Action (1)	11	Action	Capture duration of corrective actions	Represents actions to correct noted problems during tests	2	None	N/A	N/A
18	e6RBTH	Action Effective? (1)	17	OR	Decision node	RO evaluation of corrective action effectiveness	1	Probability	20	80
19	e8N361	Continue Monitoring (3)	18	Action	Action if outcome of 18 is YES	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
20	e5SHG2	Abort Required? (2)	18	OR	Action if outcome of 18 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	10	90
21	e3XDNH	Abort Test (2)	20	Action	Action if outcome of 20 is YES	Duration of actions for test abort	3	None	N/A	N/A
22	e7NZ31	Allow Test to Continue	20	Action	Action if outcome of 20 is NO	Even if corrective action was ineffective, the RO can choose to continue the test	3	None	N/A	N/A
23	e5SHG1	Problem with Environment or Test Support Assets?	12	OR	Decision node	RO decides if test assets or environment (e.g. weather, sea state) are a problem	2	Probability	10	90
24	e3X3X1	Take Available Action (2)	23	Action	Action if outcome of 23 is YES	Implement corrective actions	5	None	N/A	N/A
25	e2QWH	Action Effective? (2)	24	OR	Decision node	RO evaluation of corrective action effectiveness	1	Probability	60	40
26	e8N361	Continue Monitoring (4)	25	Action	Action if outcome of 25 is YES	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
27	e8KJBJ	Abort Required? (3)	25	OR	Action if outcome of 25 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	10	90
28	e2XZT1	Abort Test (3)	27	Action	Action if outcome of 27 is YES	Duration of actions for test abort	3	None	N/A	N/A
29	e4VY7H	Continue Monitoring (5)	25	Action	Action if outcome of 27 is NO	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
30	e21KKH	Abort Required? (4)	23	OR	Action if outcome of 23 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	10	90
31	e6S941	Abort Test (4)	30	Action	Action if outcome of 30 is YES	Duration of actions for test abort	3	None	N/A	N/A
32	e3BDH	Continue Monitoring (6)	30	Action	Action if outcome of 30 is NO	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A

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APPENDIX B. FORMAL MODEL ADJUSTMENTS FOR SENSITIVITY ANALYSIS

This appendix shows the parameter changes to two activity blocks in the formal model. These changes provided a simple method to observe the sensitivity of the model to changes in decision probability.

FORMAL MODEL BLOCK IDENTIFICATION & PARAMETERS										
Block ID	Innoslate ID	Block Label	Previous Block	Activity	Function	Description	Duration (Minutes)	Script	Probability Values (%)	
									Yes	No
1	e7N1SH	Verify Initial Conditions	None	Action	Represent overall activity of establishing necessary conditions for test	Provides duration for test event preparations	360	None	N/A	N/A
2	e20PA1	Required Initial Conditions Met?	1	OR	Decision node	RO verification that initial conditions support UUT launch	30	Probability	10	90
3	e3N61	Proceed to UUT launch	2	Action	Action if outcome to 2 is YES	Account for time necessary to provide directions to launch UUT	20	None	N/A	N/A
4	e6QR9J	Establish Proper Conditions	2	Action	Action if outcome to 2 is NO	Account for time necessary to provide directions to launch UUT	60	None	N/A	N/A
5	e7N1SJ	Conduct Test	1	Action	Overall activity for test conduct	Decomposes to various activities that represent test conduct	60	None	N/A	N/A
6	e8KW41	Begin Test Event (Launch)	5	Action	Provide starting action	Specific action in the formal model to represent test event start	5	None	N/A	N/A
7	e20CHH	Monitor Test Performance Until Test Objectives Complete	6	LOOP	Allow recursive monitoring of test sequencing	Allows model to represent RO's monitoring to the test event as the test sequence occurs	30	Continues until encountering a FALSE value	N/A	N/A
8	e3WGC2	Test Sequence Objectives Met?	7	OR	Decision node	RO verification that the test is progressing per the run plan	2	Probability	20	80
9	e8M5WH	Continue Monitoring (1)	8	Action	Action if outcome to 8 is YES	Represents duration of monitoring while test is progressing normally	3	None	N/A	N/A
10	e3XQE1	UUT Performance or Environmental/Test Asset Problem?	8	OR	Action if outcome to 8 is NO	RO decision on whether problem is UUT or Environment/Test Asset related	5	Probability	40	60
11	e7NBJ1	Evaluate UUT Performance	10	Action	Action if outcome of 10 is "UUT Problem"	Decomposes to activities supporting evaluation of UUT performance	5	None	N/A	N/A
12	e11J71	Evaluate Env. & Test Support Asset Performance	10	Action	Action if outcome of 10 is "Environment/Test Asset Problem"	Decomposes to activities supporting evaluation of Environmental/Test Support Asset performance	5	None	N/A	N/A
13	e3WT4H	UUT Performance as Expected?	11	OR	Decision node	RO decision on whether UUT performance is as expected based on the run plan and RO experience	1	Probability	90	10
14	e5T511	Abort Required? (1)	13	OR	Action if outcome of 13 is YES	If the RO observes a problem but the UUT is performing normally, he must decide if a test abort is required regardless	1	Probability	5	95
15	e11VZH	Abort Test (1)	14	Action	Action if outcome of 14 is YES	Captures duration if RO aborts test	3	None	N/A	N/A
16	e2274H	Continue Monitoring (2)	14	Action	Action if outcome of 14 is NO	Captures duration if RO continues test	3	None	N/A	N/A
17	e3X3X1	Take Available Action (1)	11	Action	Capture duration of corrective actions	Represents actions to correct noted problems during tests	2	None	N/A	N/A
18	e6RBTH	Action Effective? (1)	17	OR	Decision node	RO evaluation of corrective action effectiveness	1	Probability	20	80
19	e8N361	Continue Monitoring (3)	18	Action	Action if outcome of 18 is YES	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
20	e5SHG2	Abort Required? (2)	18	OR	Action if outcome of 18 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	10	90
21	e3XDNH	Abort Test (2)	20	Action	Action if outcome of 20 is YES	Duration of actions for test abort	3	None	N/A	N/A
22	e7NZ31	Allow Test to Continue	20	Action	Action if outcome of 20 is NO	Even if corrective action was ineffective, the RO can choose to continue the test	3	None	N/A	N/A
23	e5SHG1	Problem with Environment or Test Support Assets?	12	OR	Decision node	RO decides if test assets or environment (e.g. weather, sea state) are a problem	2	Probability	10	90
24	e3X3X1	Take Available Action (2)	23	Action	Action if outcome of 23 is YES	Implement corrective actions	5	None	N/A	N/A
25	e2QWH	Action Effective? (2)	24	OR	Decision node	RO evaluation of corrective action effectiveness	1	Probability	40	60
26	e8N361	Continue Monitoring (4)	25	Action	Action if outcome of 25 is YES	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
27	e8KJBJ	Abort Required? (3)	25	OR	Action if outcome of 25 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	30	70
28	e2XZT1	Abort Test (3)	27	Action	Action if outcome of 27 is YES	Duration of actions for test abort	3	None	N/A	N/A
29	e4VY7H	Continue Monitoring (5)	25	Action	Action if outcome of 27 is NO	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A
30	e21KKH	Abort Required? (4)	23	OR	Action if outcome of 23 is NO	If action taken is ineffective, RO must decide if test should continue	1	Probability	10	90
31	e6S941	Abort Test (4)	30	Action	Action if outcome of 30 is YES	Duration of actions for test abort	3	None	N/A	N/A
32	e3BDH	Continue Monitoring (6)	30	Action	Action if outcome of 30 is NO	Represents duration of monitoring if RO decides to test can continue	3	None	N/A	N/A

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